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MAPPING FROM SATELLITE PHOTOGRAPHY

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MAPPING FROM SATELLITE PHOTOGRAPHY

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Within the memory of many men now alive, maps were made by the ground surveyor lugging his theodolite, plane table, and alidade across the plains and up the mountains. In the years following World War II, the ground surveyor was largely replaced by the cartographic aerial camera and the photogrammetric plotting instrument. This innovation produced quantum jumps in production, geometric accuracy, and content of topographic maps.

Where Do We Stand Today

At the present time fully ninety percent of all new map compilations are produced photogrammetrically. Yet in spite of more than half a century of effort, the mapping task is woefully incomplete. Around the world only about half of the land area is covered by principal arcs of triangulation, and much less than half by first and lower order triangulation. The status of compiled maps is indicated in this table.

WORLD WIDE AND U. S. MAP COVERAGE

World Map Coverage

Quality	Small Scale 1:600,000 and Smaller	Medium Scale 1:75,000 to 1:600,000	Large Scale 1:75,000 and Larger	Remarks
Adequate	---	15%	5%	Principally U. S. and Europe
Require Revision	30%	5%	5%	
Inadequate	70%	40%	10%	
Nonexistent	---	40%	80%	

U. S. Map Coverage

Quality	Small Scale	Medium Scale	Large Scale
Adequate	100%	96%	64%
Inadequate	---	4%	4%
Nonexistent	---	---	32%

Data compiled by Army Map Service, and exclude Antarctica

Of primary concern is the fact that the rate of obsolescense of existing maps nearly equals the production of new maps, so that with present techniques the job will never be completed. Furthermore, the map production cycle is about three years from photography to printing so that the new map is three years out of date on the day it is published.

Geographers would like to see the million scale map of the world (IMW) completed. They state that most 1:250,000 maps are deficient in content. They need large scale 1:25,000 maps of all populated areas. Geologists, engineers, and other map users need similar scales. However, of first priority to all is the rapid revision of existing maps. Some sort of Parkinson's Law operates to make maps most difficult to compile and most rapidly obsolete in precisely those areas where they are needed most urgently. Maps of large urban areas should be recompiled annually. The current cycle in the United States is five to ten years.

The Gemini Photography

The use of the artificial satellite as a camera carrying vehicle is expected to provide a jump in mapping capability comparable to that which the airplane made over the ground surveyor. The Gemini photography was made with an ordinary hand held Hasselblad camera. On missions 5 and 7 photographs were made of the Cape Kennedy launch area. These two pictures, never intended for cartographic purposes, were used to revise the planimetric detail on the existing Army Map Service 1:250,000 map of the area.

In another application of the Gemini photography, the U. S. Geological Survey compiled a mosaic of most of Peru, parts of Bolivia and Chile. Control points were selected from existing 1:1,000,000 maps and identified on the individual Gemini Frames. These were then rectified and photograph tilts of as much as 40° were removed. Despite 20,000 feet of topographic relief a reasonable match was obtained, and the resultant photomap gives a view of the country never seen before.

But these are baby steps. What could be done with a system actually designed with cartographic objectives in mind?

Map Requirements

Before exploring the potentialities of space cartographic systems, it would be well to recall the requirements for producing maps.

A topographic map contains three kinds of information. The first is content, i.e., the details which are represented on the map. Content is provided by photographic resolution and scale, or more directly by ground resolution. In this area the exact capability of space photography remains to be demonstrated. For a variety of reasons it seems probable that the ground resolution obtainable with a given lens-film resolution will be higher from space than a simple geometric extrapolation from the scale of airplane photography would indicate. A useful criterion to apply is that the photography can be enlarged until its resolution is equivalent to between 10 and 20 line pairs per millimeter. This will present all the information which the human eye can extract without enlarging the map scale by magnification. Not all map information is obtainable directly from photography, regardless of its scale or ground resolution. Data such as political boundaries, place names, and detail obscured by vegetation must be compiled on the ground or from other sources. It is estimated that if the suggested resolution criterion is applied, about 80 percent of the total map information can be extracted from the photographs.

The second kind of information is the position of the objects shown on the map. For some applications the relative positions of all objects will be sufficient, but it is usually necessary and always desirable to attempt to specify all positions with respect to some well defined coordinate system, either local or national. Map positions are indicated by the reference graticule: longitude and latitude, state coordinates, or military grid lines.

The third kind of information is elevation - generally shown by contour lines above a reference surface - usually mean sea level.

In the United States, criteria for position and elevation on maps exist in the National Map Accuracy Standards. Applied to photogrammetric mapping, these standards, and the higher resolution criterion defined above, result in the values given in the following table. A fixed contour interval does not necessarily go with a given map scale. An interval fine enough to depict the terrain will be chosen.

MAP ACCURACY REQUIREMENTS

Map Scale	Std. Error Position	Ground Resolution	Contour Interval	Std. Error Elevation
1,000,000	300 meters	50 meters	500 meters	150 meters
250,000	75	12.5	100	30
100,000	30	5.5	50	15
50,000	15	2.5	25	8
25,000	7.5	1.3	10	3

The numbers in this table represent the objectives against which a space cartographic system should be evaluated.

Orbital Constraints on Photographic Coverage

It is immediately clear that if full coverage of the Earth is required, a near polar orbit is necessary. Of course, if mapping is to be restricted to specific areas, orbits of lower inclination can be employed. But for elementary discussion only near polar orbits will be considered.

An orbit is approximately fixed in inertial space and Earth rotates beneath it. At practical altitudes the satellite period is approximately 1 1/2 hours and in that time the Earth will rotate some 22 1/2° of longitude, i.e., about 2500 km. Since no reasonable camera can cover 2500 km on a

single photograph it is necessary to arrange the mission such that consecutive days will fill in the gaps. There exist so called "resonant" altitudes at 4, 145, and 303 nautical miles, at which each day's coverage would exactly duplicate the preceding day and the gaps would never be filled. In order to perform the gap filling function efficiently, it is necessary to make compromises in selecting orbital altitude, eccentricity, and inclination. Although orbits as low as 80 n.m. can be flown, for several reasons including spacecraft lifetime, an altitude of about 125 n.m. (232 km) is desirable.

As illustrated in Figure 1, the other critical parameter is the width of the ground track covered by the camera. This dimension, divided into the 2500 km between consecutive orbital passes will determine the minimum number of days in orbit which would be required to obtain complete coverage in the gaps. Quite obviously, if the spacecraft can remain in orbit for more than this minimum time, it will get more than one look at each spot. This is clearly desirable in view of the cloud cover which may be expected.

Resolution and Map Scale

The relationship between camera focal length, orbital altitude, lens-film resolution, and ground resolution is shown in Figure 2. For a wide angle cartographic camera, current technology limits average lens-film resolution to approximately 50 lines per millimeter. Thus, as indicated by line 1, a standard 6 inch camera, flying at 125 n.m. altitude, with this resolution, would produce a ground resolution of about 27 meters. Comparing this number against the resolution requirements stated earlier, it is evident that such a camera system would provide map content adequate for maps at about 1:500,000 scale. In order to obtain the 12 to 15 meter resolution required for maps at 1:250,000, a frame camera of 12 inch focal length, indicated by line 2, would be required.

To produce adequate resolution for the larger map scales with wide angle camera systems restricted to 50 lines per millimeter would

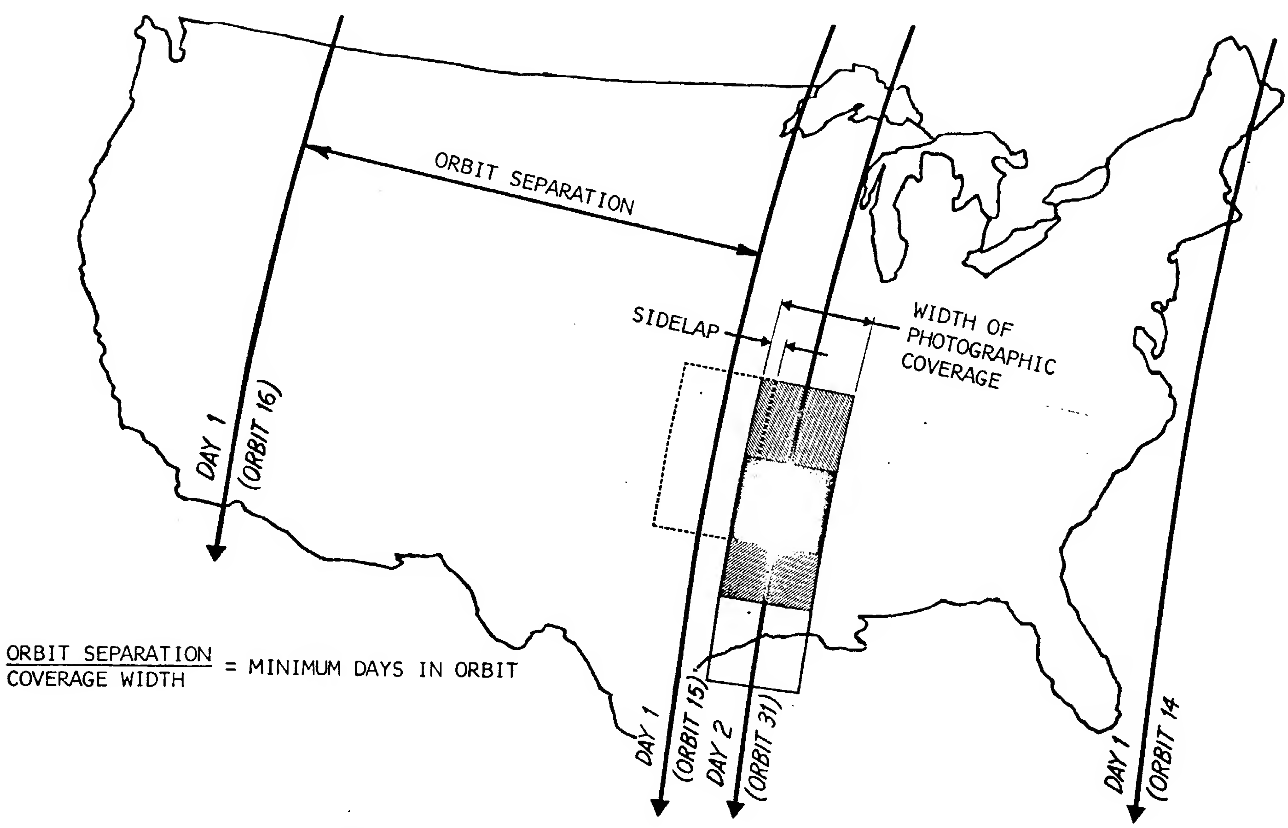

Figure 1 - Coverage of Satellite Photography

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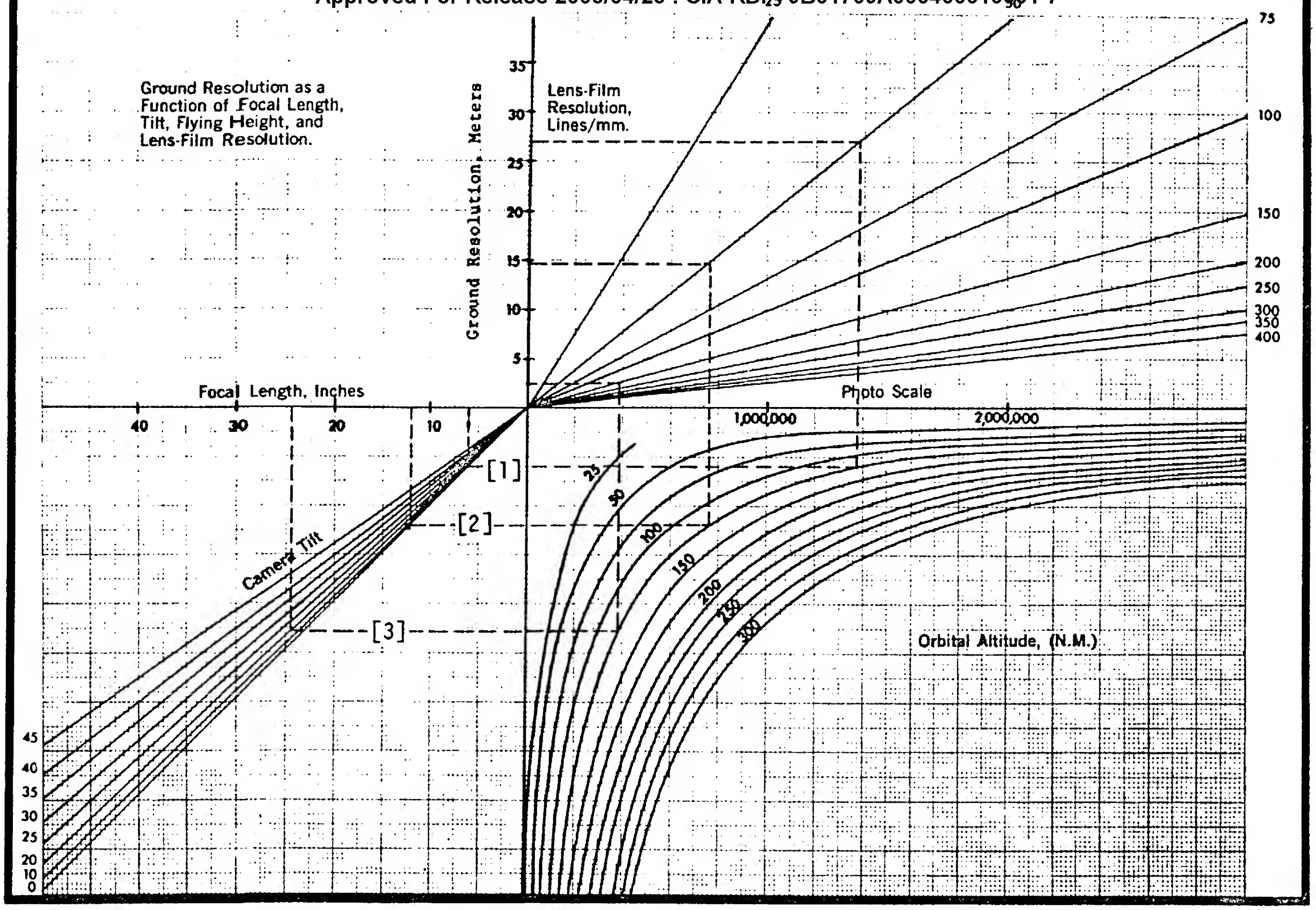


Figure 2 - Relation Between System Parameters

require cameras of extremely long focal lengths and unreasonable film formats. For this reason consideration is given to panoramic cameras which are capable of producing resolution between 100 and 200 lines per millimeter. Such cameras, however, have inherently poor geometric fidelity, and cannot satisfy the requirements for position and elevation accuracy. Line 3 on the chart shows that a 24 inch panoramic camera at 150 lines per millimeter could produce about 2 meters ground resolution - adequate for standard maps at scale 1:50,000, or, by relaxing the resolution criterion slightly, for maps at scale 1:25,000. Panoramic cameras require sophisticated and expensive photogrammetric instrumentation not generally available. For this reason an eventual operational system for producing or revising large scale maps may well go to longer focal length, narrow angle, frame cameras, which might attain 100 lines per millimeter and a corresponding ground resolution of 3.5 meters. The ground width covered by such a camera would necessarily be small. As a consequence the satellite would require a very long lifetime in order to be able to photograph any desired area with vertical pictures, or else the camera would have to take oblique pictures to the side of the ground track.

Geometric Map Accuracy

At an elementary level, the position and elevation accuracy obtainable by photogrammetric procedures is:

$$dP = \frac{H}{f}\,dx$$

and

$$dH = \frac{H}{f}\,\frac{H}{B}\,dx$$

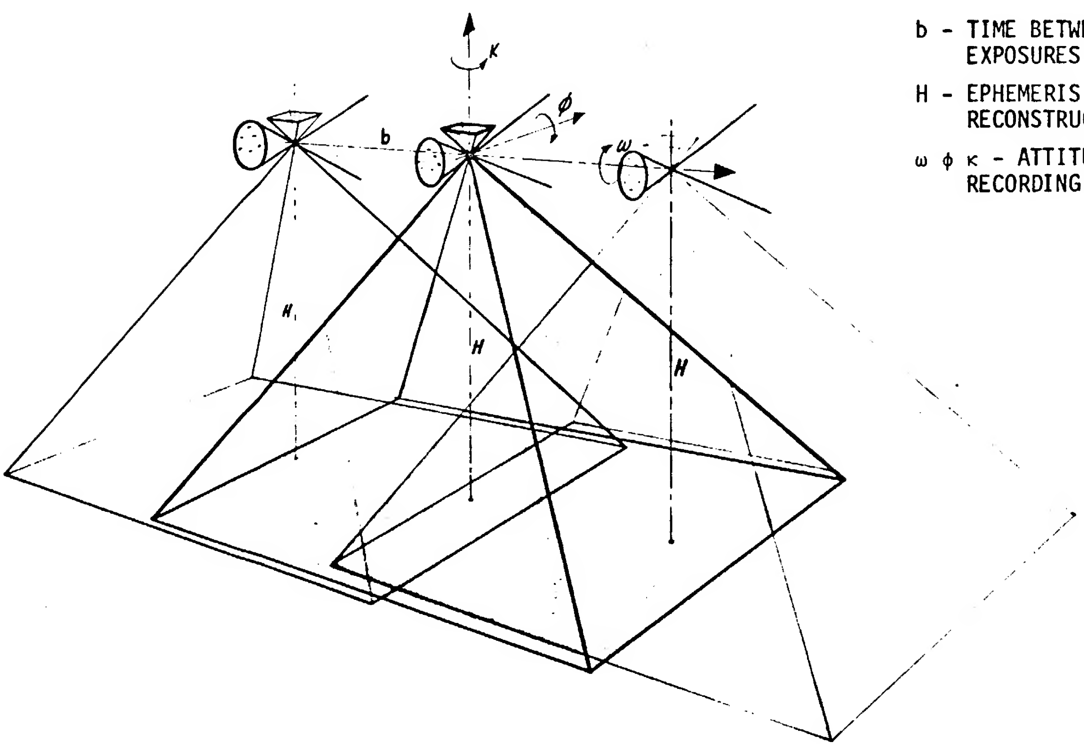
where

- dP = ground position accuracy
- dH = ground elevation accuracy
- H = flight altitude
- B = distance between exposures making up a stereo pair
- dx = accuracy of image measurement

Stereo base B is obtained by exposing the photographs at time intervals such that some part of the ground area covered by one photograph is also covered by a following photograph. With the 6 inch standard camera, consecutive photographs overlap by 60 percent and B = 0.6 H. In order to obtain adequate B with a 12 inch camera, a film format of 9 x 14.5 inches is proposed with a 9 inch dimension perpendicular to the flight direction. Consecutive photographs will overlap by 67 percent, and a stereo model will be composed of alternate photographs. This arrangement will provide an effective B = 0.8 H. Because 24 inch cameras have a narrow field of view, they cannot achieve adequate B by overlapping vertical photographs. Consequently two cameras will be required in a "twin convergent" configuration with one camera directed forward along the flight line and the other directed aft. If the angle off the vertical is 20° for each camera, the effective base in each stereo model will be B = 0.7 H.

The current level of accuracy in recovering the position of an image on a single photograph is approximately dx = 0.005 mm. This is representative of the relative accuracy which can be obtained in a single stereo model. However, as every photogrammetrist knows, a stereo model must be scaled, positioned, and levelled before geometric map data can be extracted from it. Conventionally this is done by reference to ground control, and errors accumulate alarmingly as one departs from the control.

In this regard, satellite photography will have an enormous advantage over aircraft photography. The satellite orbit is mathematically predictable, and if the time of each camera exposure is recorded precisely, the position of the camera can be accurately determined. Furthermore, as shown in Figure 3, a photograph of the star field can be made in synchronism with each terrain photograph, and measurement of the stellar photograph will provide the absolute angular orientation of the camera to a few seconds of arc. These data are equivalent to having ground control in every stereo



b - TIME BETWEEN EXPOSURES ± 0.5 MS

H - EPHEMERIS RECONSTRUCTION

ω φ κ - ATTITUDE RECORDING CAMERA

Figure 3 - Exterior Orientation of Satellite Photography

model. The consequence is that errors will not accumulate to the same extent when the photographs are triangulated in a strip or block, and a value of dx = 0.020 mm is expected to be a reasonable estimate of the absolute accuracy with which image positions can be recovered.

If the appropriate values of H, f, B and dx are applied for the three camera systems under consideration, the values listed in the following table are obtained.

GEOMETRIC MAP ACCURACY OBTAINABLE

	6 inch camera	12 inch camera	24 inch camera
Altitude H (125 n.m.)	232 km.	232 km.	232 km.
Focal length f	152 mm.	305 mm.	610 mm.
Relative accuracy position dP	7.7 m	3.8 m	1.9 m
elevation dH	12.8 m	4.8 m	2.7 m
Absolute accuracy position dP	30.7 m	15.2 m	7.6 m
elevation dH	51.3 m	19.0 m	10.9 m

If these geometric numbers and the resolution numbers previously discussed are compared with the requirements for mapping at different scales, the capabilities of the three camera systems can be summarized.

CAMERA SYSTEM CAPABILITY

Relative Mapping	6 inch camera	12 inch camera	24 inch camera
Content for map scale	500,000	250,000	25,000 to 50,000
Position accuracy for map scale	25,000	25,000	10,000
Elevation accuracy for contour interval	50 m	15 m	10 m
Absolute Mapping			
Content for map sclae	500,000	250,000	25,000 to 50,000
Position accuracy for map scale	100,000	50,000	- - -
Elevation accuracy for contour interval	200 m	50 m	- - -

The 6 inch system could satisfy the requirement for world wide small scale 1:1,000,000 and 1:500,000 mapping. The much more serious problem of medium scale 1:250,000 mapping could be satisfied by the 12 inch camera system which also has the important capability of providing adequate geometric control for the preparation of large scale 1:50,000 and 1:25,000 maps. The content for these large scale maps could be provided by the 24 inch camera systems. Thus an ideal system would be composed of both the 12 inch and 24 inch cameras. This would largely satisfy all current requirements for mapping at scales smaller than those needed for actual engineering construction.

What Are The Prospects

A year ago, the Department of the Interior announced its project EROS - for Earth Resources Observational Satellite. Although a number of proposals are under consideration, the most promising seems to be a camera system designed and built by RCA Astroelectronics Division. The camera is the ultra sophisticated child of the highly successful camera used in the now operational TIROS TV weather satellite system. The characteristics of the TIROS and the new vidicon are as follows:

COMPARISON OF TIROS AND EROS VIDICONS

	TIROS	EROS
Tube diameter	1/2 inch	2 inch
Picture area	1/4 inch square	1 inch square
Resolution	400 lines	8000 lines
Resolution elements	160,000	64,000,000
Sensitivity	0.4 ft. candle sec.	0.01 ft. candle sec.

In order to meet the requirements of a large number of scientists in the fields of agriculture, forestry, geology, geography, hydrology, and other natural resource disciplines, it is proposed to use three cameras to acquire photography in three different spectral bands.

These bands are selected to provide:

(a) The sharpest demarcation between land and water areas,
(b) The maximum discrimination of vegetation types,
(c) The greatest penetration of water.

Each frame of the proposed pictures will cover an area of 96 x 96 nautical miles and will provide a ground resolution of 100 to 200 feet from a circular orbit at 300 nautical miles. The orbit inclination will be 97° sun synchronous so that the illumination conditions will be identical for adjacent orbital passes. The satellite will weigh about 850 pounds, and can be launched by a Thor Delta from the Western Test Range. Solar cells and batteries will provide power for the cameras and for a 4 megacycle communication bandwidth required to transmit the pictures to ground stations. A video tape recorder will store the pictures until the satellite is within range of a ground receiving station. A lifetime of at least one year is planned so that repeated coverage can be obtained to determine the time variant characteristics of areas of special interest.

NASA's Lunar Orbiter program has clearly demonstrated the ability to acquire and transmit extremely high resolution photographs from space. However, photogrammetrists have learned to be suspicious of the geometric integrity of transmitted and reconstructed pictures. This fact and the lack of adequate stereo overlap makes the use of EROS photography for geometric mapping marginal.

In the Apollo program, it will be necessary to perform a number of Earth orbit missions to check out various parts of the system and procedures. NASA is studying the possibility of using one of these missions to carry a number of Earth sensing experiments. Among these would be a 6 inch focal length, 9 x 9 inch format, cartographic camera with a coupled stellar camera.

A study has been performed by Martin-Marietta Corporation to define the integration of this experiment with the other sensors and the spacecraft. They have proposed a new equipment carrier module which would replace the Lunar Module. It will consist of a welded aluminum truncated cone enclosure 84 inches in diameter at the experiment mounting end and 110 inches long overall. A truss, which will support the cone in the spacecraft adapter, will also serve to support all experiments not requiring in-flight access or pressurization. The cone itself will be pressurized and the camera system will be among the experiments in the pressurized section. The astronaut will have access to the experiment section through the air lock for such functions as changing the film magazines.

In operation the command and service module with the equipment carrier module will have its longitudinal axis normal to the Earth's surface and the cartographic camera will look down through the base of the cone. This configuration will provide the astronauts maximum terrain visibility through the Command Module windows.

The proposed parameters for the Apollo mission are:

APOLLO MISSION PARAMETERS

- Cartographic camera

  6 inch focal length, 9 x 9 inch format

- Orbit

  140 n.m. circular, 50° inclination
  (provides complete U. S. coverage)

- Lifetime

  14 days
  (provides 2 looks at every point)

- Film load

  900 frames each covering 210 x 210 n.m.
  (limited by stowage in CM for return to Earth)

- Total coverage

  13 million square miles

- Proposed launch date

  Spring 1969

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ILLEGIB

Manned missions are extremely costly to fly, and they are restricted in the amount of photographic film and other data which can be physically returned to Earth. For these reasons, NASA is also considering unmanned photographic missions, and a study has been performed by Lockheed Missiles and Space Company to define the characteristics of such a system.

NASA envisions a spacecraft, illustrated by Figure 4, carrying three 6 inch focal length, 9 x 9 inch format, cartographic cameras. The use of three cameras will provide the multi-spectral capability for resource evaluation in addition to cartography.

The exposed film would be returned to Earth in a data recovery capsule. This part of the system has been developed and proved by General Electric Re-entry Systems Division for use in several Air Force experimental programs.

The general procedure is to mount the experiment instrumentation (cameras in this case) in the spacecraft and to feed the data (exposed film) to the attached re-entry vehicle. When the data acquisition mission is completed, the recovery vehicle is separated from the spacecraft and re-enters the atmosphere. A parachute is deployed and the data package is snatched by aircraft. The spacecraft itself is then deboosted and splashes into the ocean. The recovery technology is clearly available. It remains

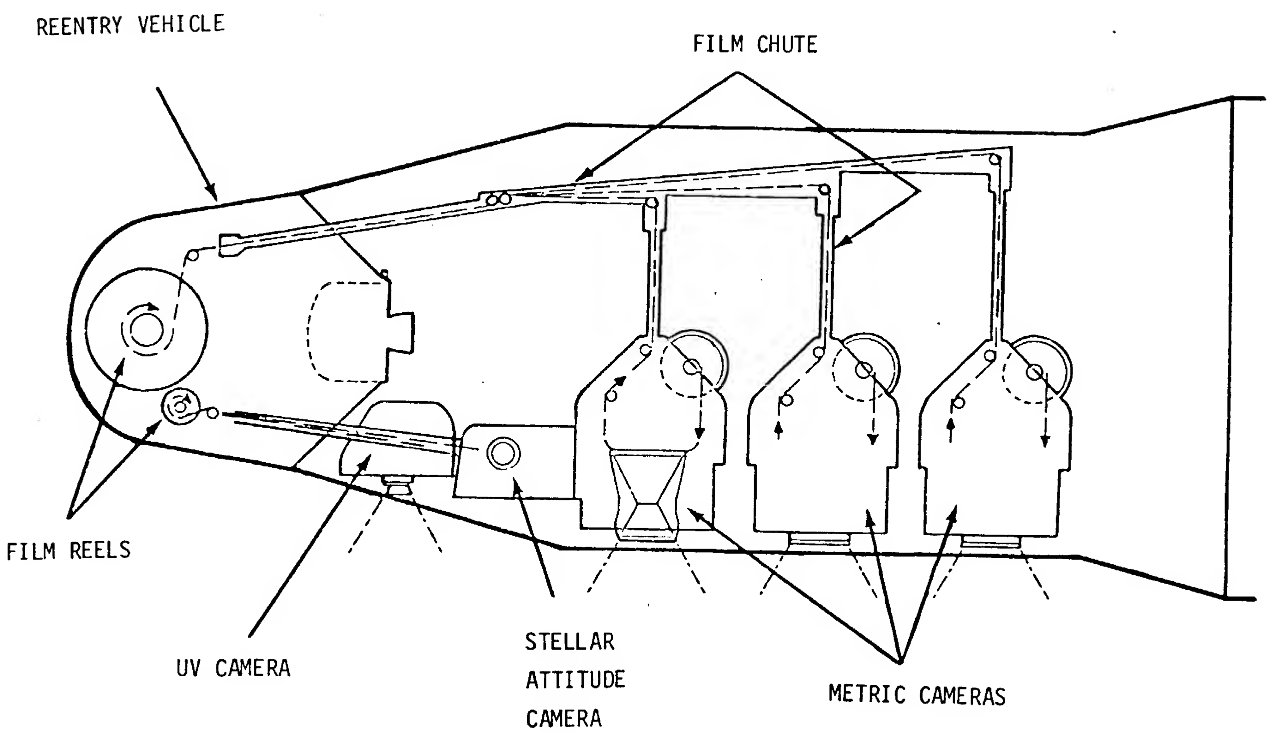

Figure 4 - Schematic for Film Recovery Satellite

to adapt the re-entry vehicle to the handling of photographic film. It is estimated that between 100 and 200 lbs. of exposed film could be returned from a single mission. With the vehicle in a sun synchronous polar orbit, with a lifetime of 3 weeks, a single camera could photograph nearly 30 million square miles. If the film load were divided among three cameras, the system could cover the entire United States in several spectral bands with a high probability of getting successful coverage.

What Are the Chances of Success

When a spacecraft is in orbit, its lifetime is necessarily limited. Since all costs have been accrued when the lifetime is terminated, the success depends entirely upon whether the mission objective has been accomplished during the lifetime. For a photographic mission, this is critically dependent upon the weather--or more specifically on the percentage of cloud free area during the daylight hours. Many studies of world wide cloud distribution have been performed, and the results of a number of them may be summarized as follows:

(1) With one look, a satellite will probably photograph 50 percent of the desired area. A second look will probably get 50 percent of the remainder; a third look 50 percent of what is left. This series would require an infinite number of looks to get 100 percent coverage. On the other hand, 4 looks would give 94 percent coverage and 5 would give 97 percent.

(2) To acquire photography at least 84 percent cloud free over the United States, a satellite launched in September would require 2 looks for the total southwest and a major portion of the midwestern and eastern sections; 3 looks would get most of the northwest but would still lose a section through Texas, Missouri, and the Dakotas.

(3) The probability of successfully photographing an area as a function of its percentage of possible sunshine is:

Percent of sunshine	Probability of success 2 looks	4 looks
Over 90	0.99	0.99
80 - 90	0.95	0.99
70 - 80	0.90	0.99
60 - 70	0.82	0.96
50 - 60	0.75	0.93

(4) The percentage of coverage with an 0.9 probability of 1 or more cloud free passes is:

	2 looks	4 looks
U. S. - summer	84%	98.5%
U. S. - winter	20	77.5
World - all year	17	65

As a generalized conclusion, these studies seem to converge on the fact that a system providing 4 looks at the areas of interest is approaching the point of diminishing returns. With a 4 week lifetime for the spacecraft, the 12 inch camera would get 2 looks, and the 24 inch camera 1 to 4 looks depending upon the configuration selected. One or two satellites would probably achieve adequate coverage of all areas which are not perenially cloud covered. To hope to photograph such areas from a satellite is probably not realistic.

Is It Economically Feasible

Presume that an unmanned satellite is launched carrying both the 12 inch and 24 inch camera systems, and that a 200 lb. film load is distributed so that both cameras would be able to photograph the same total area. Using thin base black and white film and the orbital altitude of 125 n.m., each of the camera systems would be able to photograph 9×10^6 square miles. If the total mission cost is $\$15 \times 10^6$, the photography costs $1.67 per square mile for double coverage. Even if the photography is only 50 percent useful, the cost is $3.34 per square mile.

Compared to these costs, conventional aircraft photography in the U. S. costs the U. S. Geological Survey between \$2.50 and \$4.00 per square mile on contract basis. Foreign photography, based on 650,000 square miles in South America, costs the U. S. Air Force about \$12 per square mile for single coverage. Thus purely on the basis of cost per square mile, space photography, particularly of remote areas, is clearly more economical.

The problem with these figures is that 1000 square miles from a satellite would cost the same $\$15 \times 10^6$ as the 9×10^6 square miles. Looking at the problem in this way, and using \$4 per square mile as the cost of airplane photography, the breakeven point would occur at 3.75×10^6 square miles. That is, if more than 3.75×10^6 square miles of photography are required the satellite is the economic way to get it.

The fact of the matter is, however, that the total map producing capability of the United States could not turn out 3.75×10^6 square miles of conventional mapping in a year. However, the basic reason for this is found in the number of photographs involved.

Figure 5 shows the coverage produced by conventional aircraft photography compared to that which would be given by the 12 inch frame and 24 inch panoramic cameras. Also shown is the area of a standard 1:250,000 scale map sheet.

To photograph the 3×10^6 square miles in the United States, a standard 6 inch mapping camera flown at 30,000 feet would require a minimum of 100,000 stereo pairs. The proposed 12 inch camera system flown in a satellite would cover the same area in about 500 stereo models. To process 100,000 stereo models is unreasonable, whereas 500 is clearly within the capability of most agencies.

In addition to the simple processing of 100,000 stereo models, mapping by conventional photogrammetric procedures would require several hundred thousand ground control points at about \$300 per point, whereas the 500 stereo models of space photography could be compiled with a few thousand control points. Of even greater importance is the fact that

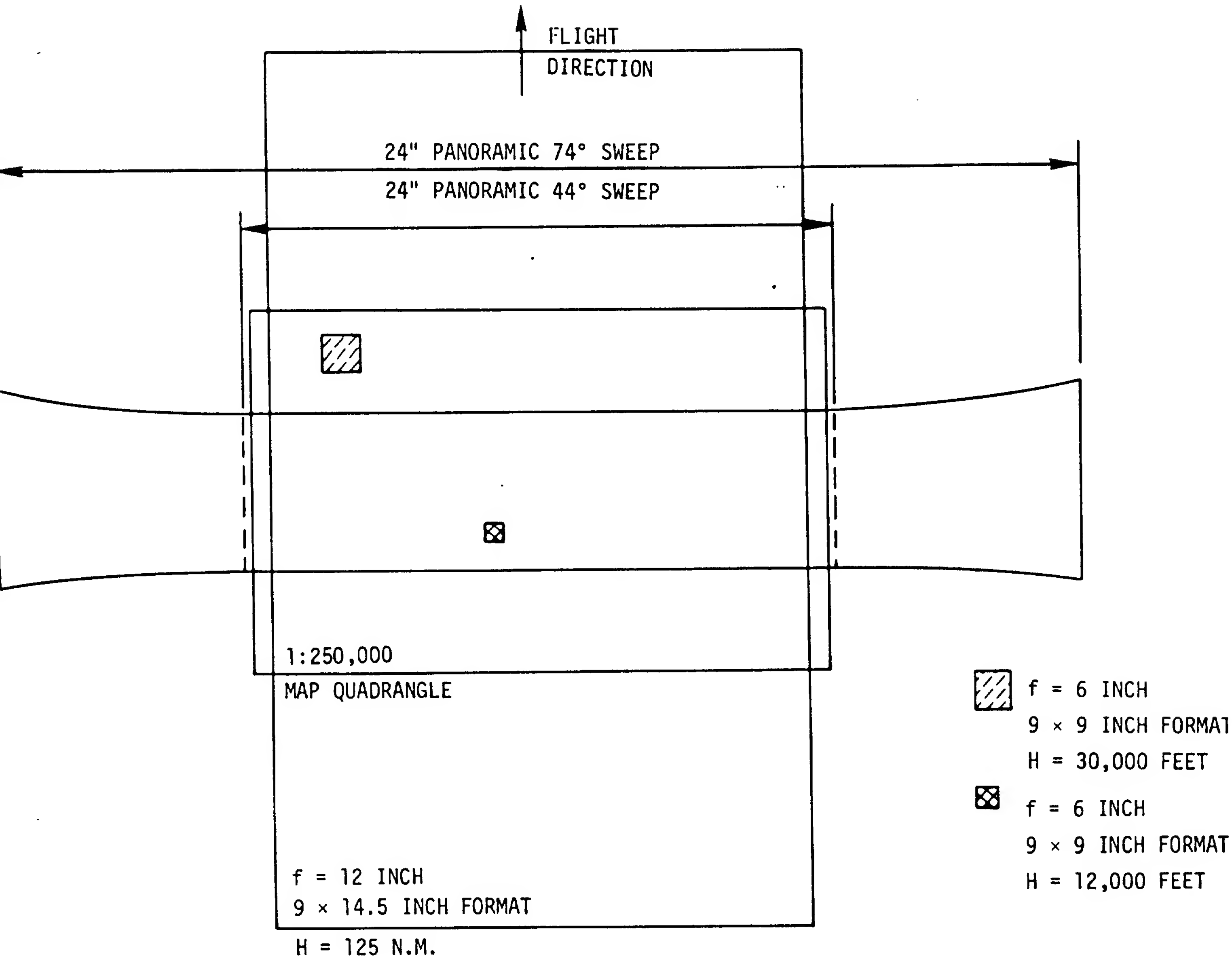

Figure 5 Comparison of Coverage Obtained
From Aircraft and Satellites

the control points for the space photography could be established by triangulation of the photographs themselves. This is not possible with the conventional photography because the errors in the triangulation accumulate with the square of the number of photographs involved. This is basically what makes it possible to predict that space photography will be able to do the job at all.

The remaining question is whether the 500 stereo pairs will do the same mapping job as the 100,000. This is the great imponderable, because there is no experience in mapping from space photography. The figures indicate that the proposed systems will probably do the job, if other parts of the mapping system are given the same attention as the spacecraft and its cameras.

The final fact is that with space photography, useful products can be made which are totally impossible from conventional aerial photography. These include:

a) A synoptic mosaic of continental areas at scale of 1:1,000,000 or 1:500,000 which is obtainable from the 6 inch photography.

b) Photogrammetric control for maps at scale 1:24,000 anywhere in the world. This is obtainable from the proposed 12 inch photography.

c) Compiled maps at scale 1:250,000 anywhere in the world. This is also obtainable from the proposed 12 inch photography.

d) Large scale, rapid response, mosaics and revised maps for any selected area in the world. These are obtainable from the proposed 24 inch photographs.

No economic analysis of space cartography would be complete without consideration of the data processing part of the map production routine. Only about one third of the current processing involves the photographs. A cartographic satellite does not improve the remaining two thirds. But it drastically alters the inputs, both in type and in quantity. The formats and focal lengths of space photography may be, to a large extent, incompatible with the current data reduction instrumentation. Clearly, if satellite photography is to be useful on a pro-

duction basis, detailed consideration and planning is required throughout the whole course of the map making cycle. This extends as far as a re-education of map users who may find it necessary to revise their notions of what is an acceptable map.

Conclusion

We see before us both an opportunity and a challenge. We have the prospect of obtaining a knowledge of the Earth's surface and its resources in detail which we could not have imagined ten years ago. Our generation may be in the position to complete the world mapping task which was started 5000 years ago when the Babylonians first put stylus to clay to guide a caravan across the desert.